An Exploratory Study of the Critical Factors Affecting the Adoption of Additive Manufacturing (3D printing) in South Africa

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Abstract

The additive manufacturing (AM) industry, commonly known as 3D printing, is an integral part of the fourth industrial revolution (4IR) and has a growing international market. South African industries have adopted AM but are not exploiting its full potential. The aim of this study was to determine the critical factors affecting the adoption of AM in South Africa, the main role players in this industry and the drivers behind the adoption of this technology.

A qualitative approach was followed, which consisted of in-depth semi-structured interviews with a purposive sample of eleven industry experts in the AM value chain in South Africa. The data were content analysed to identify the main themes, which were compared to the results of the literature review.

The critical factors in the adoption of AM in South Africa were identified as knowledge, external, financial, technical and market. The main role players affecting the AM industry are government institutions, commercial entities, RAPDASA, educational institutions and software developers. The drivers of AM in South Africa were identified as cost savings, the need to exploit South Africa's significant Titanium reserves and the ability to protect local IP (Intellectual Property).

The theoretical contribution of the study was the application of the T-O-E (Technology-Organisation-Environment) framework, as well as the practical insights of a developing industry.

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1. Introduction

1.1. Background

Additive manufacturing (AM) has rapidly transitioned from being a hobby to a tool used in rapid prototyping (Kim et al., 2008). Globally, it is seen as a viable niche manufacturing technology, and it is poised to grow by a compound growth rate of 15% (2015–2025) (Frost & Sullivan's Global 360° Research Team, 2016). Additive manufacturing or 3D printing is defined as follows: "The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" (RAPDASA, 2017).

The global aerospace, automotive and medical industries are expected to account for 51% of the total AM market by 2025. In the automotive industry in particular, global AM revenues grew at a compound growth rate of 34% from 2015 to 2020 (Frost & Sullivan's Global 360° Research Team, 2016). Considering AM's growing market share, South African public entities and research projects began investing in AM in the 1990's, and this has placed the country at the top in the global aerospace and medical sectors, specifically in terms of dental implants. Some of the factors that lend AM to both global and local implementation are the wide array of applications of the technology and materials that can be used.

Materials that can be used in AM include metals, polymers, precious metals, construction materials and high-performance ceramics. Titanium and vanadium are used particularly in the aerospace and dental industries. South Africa has vast reserves of titanium ore and is the world's second-largest producer of vanadium. AM therefore, has great potential in the local manufacturing industry (de Beer et al., 2016).

1.2. Problem Statement

Apart from AM's advantages in terms of its applications and materials, this technology can also benefit manufacturing in general through shorter lead times, tool-less manufacturing and improving time to market, among others. Programmes to support AM adoption in the above-mentioned industries in South Africa exist, especially in the formal educational sector, and in terms of creating awareness of AM in industry as well as among entrepreneurs and the public. RAPDASA (Rapid Product Development Association of South Africa), since its inception in 2000, has been created to create awareness on the potential of AM and its relevance in keeping South Africa on the world stage in manufacturing (de Beer et al., 2016). Literature on the adoption of AM in South Africa is still limited and warrants further research. Internationally, the perceived benefits and associated decision criteria for the organisational adoption of AM vary significantly across existing empirical research (Ukobitz, 2021).

Consequently, the purpose of this study was to conduct exploratory research into critical factors in the adoption of AM in South Africa. It could therefore add to the body of knowledge regarding the adoption of this technology in South Africa.

1.3. Research objectives

In light of the limited knowledge on AM adoption in South Africa, the aim of this study was to address the following research objectives:

1. To determine the critical factors for the successful adoption of AM in South Africa.
2. To identify the role players and how they influence these factors.
3. To analyse the drivers of AM adoption in the commercial field.

To effectively address the research objectives, the scope of the research was limited to AM in the commercial sector in South Africa and therefore did not focus on hobbyists and casual users of AM systems.

1.4 Layout of the paper

The following section 2 reviews the prior studies on the topic, including the history of AM, the factors influencing the adoption of AM and the key role players. Section 3 outlines the methodology for the research of this study, Section 4 the Results of the analysis of the data, Section 5 the Managerial implications, Section 6 the Conclusions, Limitations and Recommendations for future research.

2. Literature Review

The literature review is divided into the following sections: the history of AM, factors influencing the adoption of AM internationally and in South Africa, role players in the South African AM industry and technology adoption theories.

2.1. History of additive manufacturing

The stereolithography machine, an early incarnation of the 3D printer, was patented in 1986 by Charles Hull (Matias & Rao, 2015), who subsequently filed many other associated key patents. AM technology has developed rapidly and many techniques to implement it were developed. Machines were used, mostly by engineers, for prototyping purposes during that era. AM took an interesting turn when, in 2005, the RepRap machine (Jones et al., 2011) was developed within the open-source community. This was the 'Holy Grail' for the tinkerer. The MakerBot (West & Kuk, 2016) followed in 2009 and obtained market traction and consumer awareness. Many other printers were developed internationally. The RoboBeast printer (Vermeulen, 2014) was developed in South Africa.

The AM process generally begins with the creation of a computer-aided design (CAD) file that represents an object. The data are stored in a standard tessellation language file. This virtual object is then sliced horizontally by the CAD software, and each slice is sequentially fed to the computer-controlled head of the printer that deposits material on a surface to physically create that layer. As layers are deposited sequentially on top of each other, the object is built from the bottom up and the object is created (Figure 1).

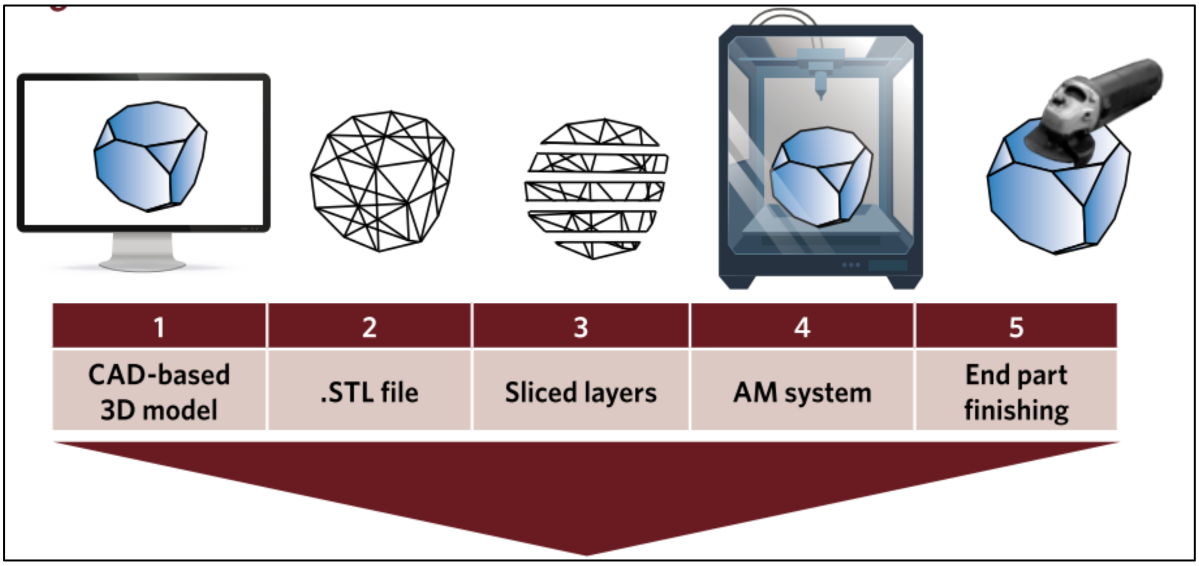

Figure 1. The additive manufacturing (AM) or 3D printing process.
Source: Vitale et al., 2016.

Since the inception of AM, various techniques to deposit material during the printing process have been invented (Vitale et al., 2016), for example:

- Vat photopolymerisation, during which a liquid polymer (plastic) in a vat is selectively cured using light;
- Material jetting, where a printing head is used to deposit material on a surface. The deposited material is subsequently cured using ultraviolet light;
- Material extrusion, where a heated nozzle is used to deposit a thermoplastic material on a platform. This deposition process continues until the 3D object is created;
- Powder bed fusion, during which material particles are fused using heat from a laser beam. After the layer is created, a new powder layer is deposited and the new layer is fused again. This process is continued until the 3D object has been created;
- Binder jetting, where powdered material is coalesced together using liquid glue. Once the layer has been created, a new powder layer is deposited and the process is repeated until the desired object is created;
- Sheet lamination, during which sheets or laminations of plastic or metal are bonded together to form an object. A laser beam or knife is then used to cut off the unwanted material. A new layer is added on top of the previous layer and the process is repeated until the desired object is completed; and
- Directed energy deposition, where a thermal energy source is used to fuse metal together as it is being deposited.

One of the limitations of AM systems is the limited number of materials that can be used during the 3D printing process. Materials used include photopolymers, thermoplastics, titanium, paper, plastic, ceramics and other metals and metal alloys. Recently, developments in 3D concrete printing have highlighted the benefits of a lower climate change impact (Alami et al., 2023). However, there are still issues that need to be addressed such as material incompatibility and the cost of the materials (Jandyal et al., 2022).

The main opportunities for implementing additive manufacturing in South Africa are the following (de Beer et al., 2016):

- Medical /dental / hearing aids/footwear;
- Aerospace / automotive / tooling;
- Jewellery;
- Robotic components;
- Consumer goods (cell phone covers); and
- 3D printing of archaeological artefacts.

The main benefit of AM in the businesses listed above is the ability to customise items.

2.2 Factors influencing the adoption of additive manufacturing

There are several factors driving the adoption of AM, but also a number of factors inhibiting the adoption, which have been highlighted by Ukobitz (2021) and are discussed below.

2.2.1 Factors enabling consumer adoption of additive manufacturing

The following factors were identified:

- Rapid prototype design and production: AM reduces the time from visualisation to the prototyping of parts and assemblies, and finally to production (Frost & Sullivan's Global 360° Research Team, 2016; Tam & Lung, 2023; Rose & Bharadwaj, 2023). This process has been adopted by leading car manufacturers, such as BMW and Ford (Frost & Sullivan's Global 360° Research Team, 2016);
- Customisation capacity, flexibility, and complexity: The production of complex parts that cannot be easily manufactured by conventional methods is now a reality with AM, which can help transcend the existing design and manufacturing industry (Jiménez et al., 2019). This is especially important in the medical and dental industries (Manyika et al., 2013). For example, dental implants and hip joints can be made using AM techniques;
- Reshaping the supply chain: AM can reduce manufacturers' inventories of parts and objects, which can be printed when and where required. Manufacturers only need to keep blueprints of the objects required. This advantage is especially relevant to the production of car seat parts for Toyota (Thewihsen et al., 2016; Ekren et al., 2023; Besklubova et al., 2023); and

- Cost effective manufacturing and non-wastage: AM is seen as a manufacturing technology that could reduce costs in the future, because less labour will be required to manufacture objects (Frost & Sullivan's Global 360° Research Team, 2016). Another advantage of AM is the low waste generated during the manufacturing process, as opposed to traditional manufacturing, where excess pieces are cut or removed, the additive process uses material only for the part itself, thus creating immense savings (Leering, 2017; Besklubova et al., 2023).

2.2.2 Factors inhibiting consumer adoption of additive manufacturing

The following factors were identified:

- Skills development, training and experience: One of the main inhibiting factors of AM being adopted is training and skills development, which are crucial if AM is to be successfully adopted (The Boston Consulting Group, 2016; Belhadi et al., 2022). This will require a change in mindset and the acquisition of up-to-date skills. Importantly, the investment by industries in traditional manufacturing equipment and the necessity to recoup the cost is an inhibitor in the adoption of AM (Leering, 2017);
- Build-speed time and energy requirements: Building a part using AM is still too time-consuming, which is not acceptable in many industries. However, this is not the case for all AM techniques (Laser, 2017). Nonetheless, in this regard, traditional manufacturing techniques are still preferable and cannot be replaced by AM technologies. The energy consumed to create AM designs is also significant in some cases;
- Size, quality and standard of parts manufactured in AM: The size and strength of the parts that can be manufactured through AM limit what can be produced and where they can be used (Vitale et al., 2016). This issue is more prominent in certain versions of AM, such as bed fusion (Laser, 2017). A lack of standards also inhibits the adoption of AM (Reeves & Mendis, 2015a; Rathore et al., 2022);
- Price of raw materials and printers: Currently, the high price of raw materials and industrial printers inhibit the adoption of AM (Leering, 2017). The high cost of creating 3D CAD files should also not be underestimated and contributes to the lack of AM adoption (Yee, 2016). However, through the use of low-cost scanning technology, the cost of CAD file creation is declining (Yee, 2016); and
- Management education: Industrial management professionals' awareness regarding AM is lacking and seen as inhibiting AM adoption. A transformation roadmap is required for AM to be explored and implemented (Thewihsen et al., 2016; Rathore et al., 2022).

2.3 TOE Framework for analysing technological adoption by organisations

The TOE framework (Figure 2) was developed by Tornatzky (Tornatzky & Fleischer, 1990), to improve understanding of the adoption of technology by organisations, and subsequently promoted by Miscione and Johnston (2010). It consists of three dimensions for analysing an organisation's potential to adopt technology (Alshamaila et al., 2013; Low et al., 2011; Ngo et al., 2023).

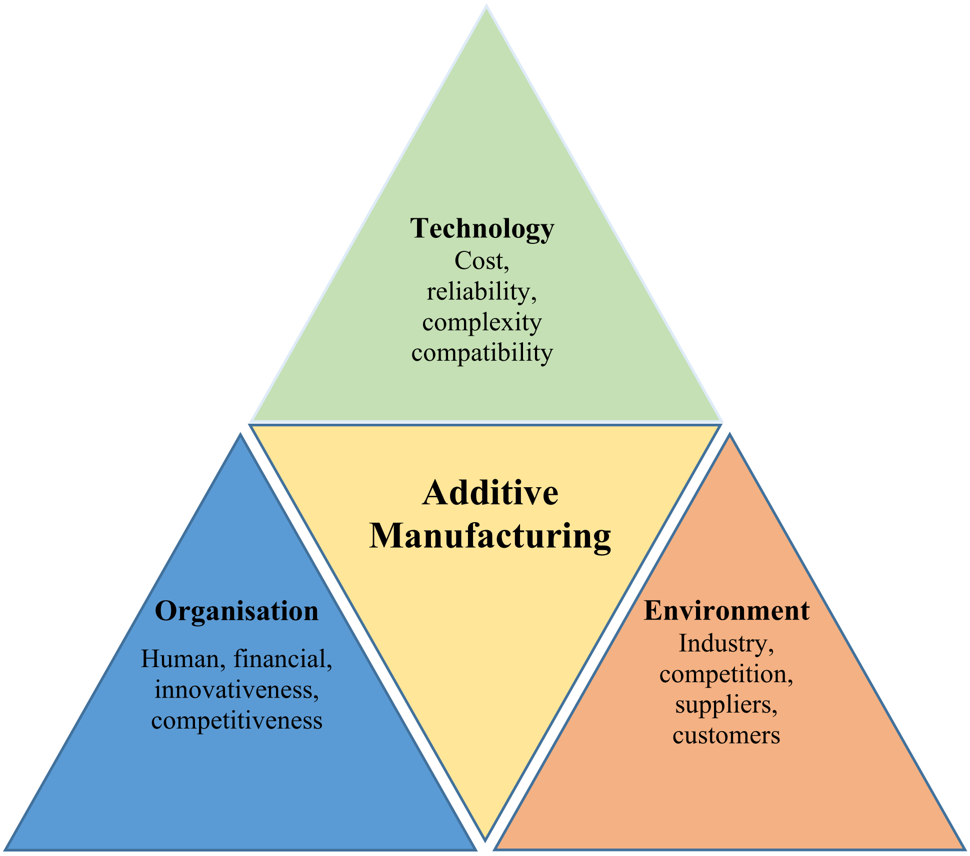

Figure 2. The Technology–Organisation–Environment framework used to understand the adoption of technology by organisations (Miscione & Johnston, 2010)**.**

Technological context

The technological dimension of the TOE framework represents the internal and external technologies that are used or not in the organisation (Miscione & Johnston, 2010). The technology not yet used influences adoption by setting limits for potential innovation. Innovation can vary in pace and degree, and there are associated risks with each of them. The major factors include technological complexity, compatibility with existing technology, perceived reliability and costs (Miscione & Johnston, 2010). The ability of an organisation to reduce operational costs and hence increase relative business profits is also seen as a crucial factor in its relative success (Yeh & Chen, 2018).

Organisational context

In the organisational dimension of the TOE framework, the structure and size of an organisation determine its ability to innovate. The human and financial resources available at an organisation are important in this regard (Miscione & Johnston, 2010). Organisational readiness from the viewpoint of managers is important to support the adoption of new technologies (Yeh & Chen, 2018). Prior technological experience at the organisation is another deciding factor in the ability of an organisation to adopt new technology (Alshamaila et al., 2013). Research by Florén et al. (2021) suggests that the adoption of AM will require firms to rethink how they do business – specifically how they adapt their existing production systems when implementing AM technology.

Environmental context

The environmental context involves the greater environment in which the organisation runs its activities. Strong competition between players in the same industry encourages innovative change (Miscione & Johnston, 2010). Other important factors in this context are the scope of the market and the suppliers to the organisation (Alshamaila et al., 2013). The main factors that influence the adoption of AM can be classified in the TOE framework (Table 1), which has been used to analyse factors driving the success of AM adoption (Yeh & Chen, 2018). For these reasons, the TOE framework was used to study the adoption of AM in South Africa.

Table 1: Factors influencing the adoption of additive manufacturing in organisations according to the Technology–Organisation–Environment framework.

Technological context	Organisational context	Environmental context
Rapid prototyping	Cost-effective manufacturing	Intellectual property issues
Part size	Reshaping the supply chain	Ecosystem
Part quality	Skills development, training, and experience	Management education
Build speed		Price of printer
Wastage of raw materials		Cost of raw materials
Energy requirements		
Customisation capacity		
Capacity of making complex designs		

2.4 Role players internationally and in the South African additive manufacturing industry

Internationally, the AM industry is still seen as being in its infancy and the key actors are from a very broad spectrum of industries (van der Zee & Rehfeld, 2015).

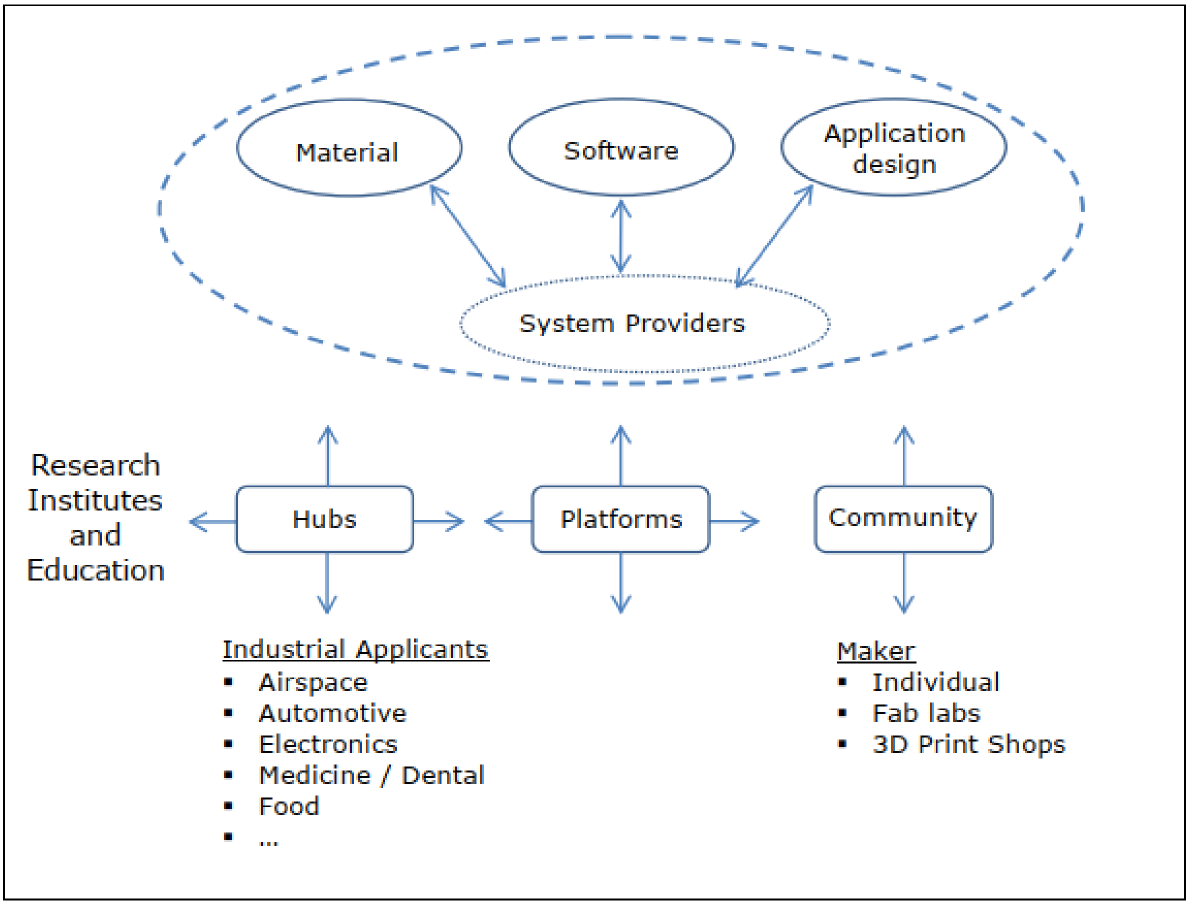

Figure 3: Role players in the AM industry
Source: *van der Zee & Rehfeld, 2015.*

As seen from Figure 3, there are four groups of actors operating in this landscape:

- System providers that directly develop AM machines, materials used, software and related matters. These companies are not vertically integrated and source components from manufacturers;
- The second group are the research institutes and educational institutions. Topics of basic and applied research related to AM such as rapid product development, tooling, design of medical devices, 3D scanning etc are being taught;
- The third group are the industrial applicants that are applying AM in different fields. The biggest industries internationally in this field are industrial business machines, aerospace, motor vehicles, consumer electronics and medical and dental applications (van der Zee & Rehfeld, 2015); and

- The fourth group are platforms and communities that bring together all the actors in this field.

Not much literature is available on AM in South Africa, and existing literature mostly stems from the educational or academic landscape. The Rapid Product Development Association of South Africa helps to promote AM in the industrial landscape (RAPDASA, 2017); (Klenam et al., 2022). The role players interviewed in this study were identified from key industries based on international literature (de Beer et al., 2016) and involved the automotive, aerospace, consumer goods, creative, defence, energy, medical, dental, research, small and medium enterprise, tooling and refurbishment and sporting and leisure goods industries. The aerospace, military, medical, dental and manufacturing industries are prominent in the South African AM space (RAPDASA, 2017).

2.5 Drivers of AM internationally and in South Africa

The capacity to produce complex designs is the key factor in AM adoption (Niaki et al., 2019). This provides many benefits in terms of sustainability. It has been noted that AM is more environmentally friendly than machining (Faludi et al., 2014). Moreover, AM brings benefits at the multiple stages in the design of an object, namely the material processing, the ability to make objects on order and the ability to reuse designs (Ford & Despeisse, 2016). All these stages save time and money and thus contribute to the sustainability of a firm.

In the medical market, for example, there is a need to produce parts with unique shapes and high functionality in a reasonable amount of time. However, the motivation varies across sectors, and production costs do not rely on the design complexity.

AM boosts creativity and innovation through free-form fabrication. The drive for companies to become more competitive internationally in a harsh global economic environment has pushed for higher levels of innovation in manufacturing, which can be achieved via AM adoption. The competitiveness translates into increased trading with other nations, which can boost revenue. The majority of companies adopt AM for time and cost savings, particularly for new product development, customisation and low-volume production (Niaki et al., 2019). In South Africa, the adoption of AM has been driven by the potential commercial and performance benefits the technology brings, especially in the aerospace industry (Blakey-Milner et al., 2021). In this industry, the drive to continuously improve efficiency through cost reductions, lead-time reductions, lowering of the mass of flight components, and the use of high-performance materials in increasingly complex designs is seen as a driver for AM adoption (Blakey-Milner et al., 2021). As seen in (Dimitrov et al., 2018), the manufacturing of titanium-based parts for the aerospace industry in South Africa are using AM to create a more sustainable process and thus remain competitive on a global scale. The South African railway industry is also experimenting with AM to reduce their costs and reduce lead-time for spare parts (Toth et al., 2022).

3. Research Methodology

3.1. Research approach and strategy

As there is relatively little research on this topic, particularly in South Africa and given the relative infancy of this industry, an exploratory approach was adopted, utilising a qualitative strategy with an inductive methodology and a cross-sectional approach.

3.2 Population and sampling

The study population comprised the main role players in the South African AM industry. Since there were likely to be few AM experts in South Africa, purposive sampling was used. The limitation of this approach is that it cannot yield statistical inferences about the population (Greener, 2008). Snowball sampling was subsequently used, as this allowed for data collection via a referral network.

Interviews were conducted until saturation was achieved. It has been noted that overarching themes can be developed after six interviews (Guest et al., 2006) and that after twelve interviews all the major themes were discovered and saturation was reached. It was therefore determined that between six and twelve interviews should be conducted, with an actual sample of eleven being achieved.

3.3 Data collection

Eleven usable in-depth interviews were conducted by telephone, and the conversations were recorded with the permission of the interviewees. The interviews lasted between 20 – 60 minutes each and were scheduled at a time suitable for the participant. The research instrument was a semi-structured interview schedule to probe the research questions related to AM adoption in South Africa. This instrument allowed communication between the interviewer and interviewee to be open-ended and to focus on important topics as they arose during the interview (Adams et al., 2007). Semi-structured interviews were conducted and were not standardised. Participants had the freedom to answer the questions in any order they preferred, as this helped the conversation to flow freely.

3.4 Data analysis

Data collected from interviews were transcribed verbatim, using Trint and loaded into qualitative data analysis software NVivo22. Open and axial coding were used to analyse the data (Kaiser & Presmeg, 2019) and a hierarchy of codes was created. This content analysis identified themes during the open and axial coding processes which were then linked to factors identified via the literature review.

3.5 Research criteria

For quantitative research, the issues of validity and reliability are critical. However, for qualitative research, it is important to ensure trustworthiness in data collection and analysis (Cresswell, 2014). The trustworthiness of qualitative research can be assessed by four qualities (Forero et al., 2018), namely:

- Credibility;
- Dependability;
- Confirmability; and
- Transferability.

These aspects were developed by Lincoln and Guba (1986), as cited in Forero et al. (2018). Firstly, the researcher digitally records all the interviews done and keeps them in a secure location, not accessible to the public. The details of the interviews are kept in case it needs to be referred to. To ensure that the findings are dependable, a standard set of questions are asked to each interviewee. To foster credibility in the study, key stakeholders in the sector were interviewed. To ensure transferability of the research, the researcher kept enough information on the interviewees and the setting in which the study took place. To ensure authenticity, quotes from the interviewees were used in the report.

3.6 Ethics

This study adhered to the University of Cape Town's Graduate Business School procedures regarding ethical research, and from which ethical clearance was obtained. No ethical constraints needed to be addressed in this research. Participation was voluntary, the participants' names remained confidential to protect sensitive business information, and anonymity was assured. All the digital records were kept in a secure location, inaccessible to the public.

4. Results and Findings

4.1 Respondent demographics

The interviewees comprised the following role players:

- AM machine resellers;
- AM printing material, accessory, and software resellers;
- Service providers in civilian and military sectors;
- Industrial project manager; and
- Artist/creative professional.

The service providers had extensive experience in the manufacturing industry and have been working specifically in AM for over 30 years. The machine resellers have sold over 6000 3D printers, encompassing a broad range of instruments in terms of material used and price range. Some of the interviewees fulfilled multiple roles in the AM value chain.

4.2 Critical factors for successful additive manufacturing adoption

To address the first research question, content analysis identified that the most important factors affecting the adoption of AM in South Africa were: knowledge, external factors, financial factors, technical and market. These are elaborated on below.

Knowledge

Knowledge was the most important aspect when considering the adoption of AM in South Africa. Different aspects regarding AM education were mentioned by the interviewees. The following sub-themes were identified under the main theme of 'knowledge':

Theme – Understanding the value of AM at the management level

Participants emphasised a lack of understanding at the management level of how investment costs regarding expensive additive printing machines can be recouped. An understanding that investment in expensive equipment, supported by a good business plan, can be profitable in the long term, such as with other industrial machinery, is also lacking. This lack of awareness of AM among business leaders on the global stage has been identified as an important factor in the adoption of AM (Thewihsen et al., 2016). This is highlighted by some comments from respondents in Table 3:

Table 3: Theme – Awareness of additive manufacturing at management level

'I think probably a lot of businesses need to be aware of what it [AM] can do for them and maybe then they'll take that jump.' **Managing director – service provider**
'And then also you need to go out there with awareness, is one thing, but you need to actually show the new applications, go and spend time with the design engineers inside companies to say, "Okay, this is your problem ultimately to solve; this is how we can solve this.'' ' **Managing director/researcher**
'You know, there's a lot of interest in 3D printing but no real understanding of how it could benefit their business as such. So there is a lot to do there. So we need to get out to businesses and look at their current processes, and then they need to be educated: "This is how 3D printing will benefit your business. You will be able to produce parts x amount quicker, x amount savings on materials," and so on.' **Managing director – service provider**
'We get a lot of buzz. They want a 3D printer, but they don't really know why. They know they have to get into it. But they are unsure why exactly they buy that.' **Managing director – service provider**

Theme – Awareness of AM at secondary/tertiary/continuous learning education levels

Knowledge about AM is also lacking at the primary, secondary and tertiary education levels. The respondents compared South Africa to educational establishments in the United States and Europe, where learners and students are exposed to AM very early on. Lack of skill and training development was mentioned in the literature as a barrier to AM adoption (The Boston Consulting Group, 2016). Another aspect of AM that was noted is that teachers are not well-trained to teach this topic. The poor digital culture and skill deficiency among the youth in South Africa has been noted as a barrier to the adoption of 4IR and thus AM (Mtotywa et al., 2022). This theme is highlighted by some comments from respondents in Table 4:

Table 4: Theme – Awareness of AM at secondary/tertiary/continuous learning education levels

'I think it's still sort of seen as very exclusive, so we're not seeing, like in the US and Europe, where we see at school level, primary school, even then secondary school, where students are getting access to 3D printing. We are seeing it slightly now, but more in the private schools and so on. Universities are also very exclusive to the engineering departments and so on, so I think there could be more done.' **Managing director – service provider**
'We have funding, a lot of it goes into education, particularly on the university side. I think it should be more in schools. But at the moment, the school curriculum is the difficulty. The teachers don't have all the training, and the curriculum is not set, and it's quite hard for them to get and justify using a 3D printer.' **Managing director – equipment/material supplier**

Theme: Change in mindset required to adopt AM

The need to change the thought process when designing for AM was mentioned almost invariably by all the interviewees. The designs needed for creating parts via AM are different from those for traditional manufacturing techniques. Furthermore, the current training in AM is too focused on the mechanical aspects of making parts, such as the material being used, or the operation of the AM machine itself and not on the design of the parts to be created. Internationally, it has been found that the training of young engineers, in the field of AM at the university level, benefits them in terms of personal preparation and improving their skills (Motyl & Filippi, 2021). Respondent quotes illustrate this theme in Table 5:

Table 5: Theme – Change in mindset required to adopt additive manufacturing

'And, you know what, art is art. Like paint a picture. It's, I think the thing is, [in] engineering [it is] three is three, you know. Whereas in art, there is no answer; there's no answer. You have to, it's almost like a research thing. It's, like, nobody can tell you if you're right or wrong. You know, I think that's why the art is valuable, you know, because it's. Yes there's no right. You just go on. So in an uncertain future, where you don't know what is one plus one what is the answer. You be able to do something where there is no answer. I'm trying to get better at it, could be it, would be, yes. And that's why 3D printing, it's useful to have an open mind to possibilities that are weird, because some of them might be very interesting and some are crap, and I think that's where the engineering and the technical things comes to sort the crap ideas.' **Artist**
'There's a big focus on how a machine works: the hardware, how quickly does it print, what

resolution? Where 3D printing is interesting is that there is a massive, the biggest, amazing part of it is the design part. Like, it enables one to do different things for mass manufacturing. That is a kind of a way of thinking that's not trained; the new stuff, if you want to also encourage the creative side, creative innovative side. Literally, visual skills, 3D skills, you know, those are not typical things that you are trained in engineering.' **Artist** 'You know there's a philosophy of everyone wants a 3D printer; okay, so? But people don't understand that there's a complete change in mindset needed in how are parts designed or manufactured, or not manufactured. You need to start designing your end product differently if you're going to be adopting 3D printing, okay?' **Managing director – service provider**

External factors

External factors that were mentioned in the interviews were the risks of doing business in the current South African landscape, IP rights, the regulatory environment, and standards of manufacturing. A lack of standards has been noted in the literature as a barrier to AM adoption (Reeves & Mendis, 2015b). Moreover, small organisations cannot fight copyright infringement (Veer et al., 2016). (Roberts et al., 2021) noted how uncertainties in the macro-environment affected the purchasing behaviours of organisations, which is not specific to the AM industry. In Mukwawaya et al. (2018), it has been noted that South Africa's policy is not ready for the adoption of 4IR, of which AM is a fundamental part. The regulatory issues are highlighted in Table 6:

Table 6: Theme – Regulatory issues in the adoption of additive manufacturing

'There is no regulation as such. There is a potential problem of infringing copyrights and patents and so forth. Yeah. We've never come across it. We've never been contacted by anyone saying "Ah, you guys are printing stuff you're not supposed to be printing." There's nothing being enforced.' **Managing director – service provider** 'Intellectual property issues I would say. The big thing for me in the small area is it doesn't matter if I have IP – I can't defend it. So I think that is, oh, get a patent or something. It's, like, okay, fine, I have the patents or creative works, but so what if somebody in Italy decides to download and print out? What am I going to do in South Africa?' **Artist** 'Yes, for sure. So as I said, ISDM, ISO [International Organization for Standardization] is doing a lot of work in terms of standards and trying to do that. They've written quite a lot on, actually, in both ISDM and ISO, and through them we've tried to get SABS involved as well, but they are not commenting at this point on the technology. I think there is some scope for improvement in South Africa to at least get a technical committee involved in this development, because as it's critical,

especially on metals.' **Managing director/researcher** 'Well, we hold ourselves to a certain quality control or manufacturing standards. But I do believe that, in the future or very near future, they will become an issue whereby you know three different 3D printing companies are making the same part roughly, with large variances in terms of the quality between them. So it'll have to be some kind of point where 3D printing is standardised and sits within certain regulations.' **Managing director – service provider/material supplier** 'At the moment, 3D printing in South Africa is essentially unregulated. If three people make the same product, there can be an incredibly large variance between the three. In the Western world, I understand they are held to a certain standard with each component.' **Managing director – service provider/material supplier**

Theme: Political instability

The other external factor that prevents industrialists to invest in South Africa is the political instability in the country as can be seen from this quote below:

'Look, I deal with a lot of engineering companies on a daily basis. And what I'm finding is they really are reluctant to invest in the technology at the moment, purely because of the political situation in South Africa. A lot of my customers are leaving the country. They are moving their factories overseas to America, New Zealand, Australia.' **Managing director – equipment supplier**

Financial factors

The initial capital required to invest in a 3D printer and its related infrastructure was the most frequently mentioned factor in terms of financial issues, as noted in the literature (Ford & Despeisse, 2016) and as highlighted in Table 7:

Table 7: Theme – Cost of additive manufacturing equipment

'Capital investment would have been our biggest barrier to getting it right.' **Managing director – service provider/material supplier** 'The barriers to entry for me are cost.' **Managing director – designing service/service provider** 'So I think the biggest challenge, the machines, the high-end systems, are still very expensive. The raw materials are very expensive. And to justify, you know, to buy a R 5–10 million machine, we need to do a large amount of already work with this service.' **Managing director/researcher**

Other associated prohibitive costs that were mentioned were the following: software for the design and simulation of AM parts, ISO certification is needed in the production of medical-grade parts, and the cost of raw materials, which are mostly imported. The high costs of raw material has been noted in the literature (Leering, 2017); (Yi et al., 2021).

Technical factors

Technical issues related to software were sorted into three sub-themes: software to control 3D printers, established software to design new products, and custom-written software to function in niche markets. The software to control 3D printers comes with hardware provided (i.e. the 3D printer) and is usually not difficult to operate once it has been learned. Software seems to be a corner stone of AM, as it is developing rapidly to provide novel solutions and the lack of specialised software was also noted in the literature (Gao et al., 2015). This is illustrated in the comments in Table 8:

Table 8: Theme – Software required for additive manufacturing

'The software is developing very rapidly. And I think that's actually where the power of 3D printing will eventually lie for businesses. So again, printing is just another manufactured technology.' **Managing director/researcher**
'For me, the specialised software is overpriced and without a lot of advantages to it. I mean, we've engaged with the various software companies, and it's, you know, too expensive. At the moment, the market in South Africa is, in my opinion, there needs to be a lot more manufacturing houses and manufacturing hubs before the software industry can lay claim to the claims that they're already making.' **Managing director – designing service/service provider**
'If you think, for example, like, the way they produce insoles or whatever the case may be. Yeah, the business is not the 3D printer. The business is having a scanning tool that allows you to scan someone's feet, examine the software suite that converts that from scanned data into something printable, and the IP [intellectual property] is there. Same for software where they scan your teeth. They make tools and all of that. All those almost unique IP things. Those killer apps, if you want to call it.' **Managing director/researcher**

Other technical factors mentioned included the cost and availability of raw materials, the shelf life of materials, as is the quality of locally produced materials, which in some cases are inferior to imported products.

Market

The market was not seen as a big barrier to the adoption of AM as opposed to the previous factors. However, it was pointed out that the market for AM was not big enough in South Africa, but competition with China is also of concern as they can be very cost-effective (Berman, 2020). Relevant comments from respondents are given in Table 9:

Table 9: Theme – Market-related issues in the adoption of additive manufacturing

'At this point in time, we, to some degrees, are removing Chinese manufacturers from the equation, because we are able to manufacture the equivalent products in the same material specs locally at a fraction of the price, which is a huge step forward, because, generally speaking, China's always been the leader of the pack, so to speak. They can accommodate scale for very low prices.' **Managing director – service provider/material supplier**
'And I also think a lot of companies, they don't want to buy into the technology, because the market is not big enough to carry them in terms of maybe being a bureau for printing.' **Managing director – service provider**
'We are small. We are far away.' **Managing director/researcher**

4.3 Role players

This section addresses the second research question which is about the main role players in the AM industry and their influence on AM adoption, which were identified as follows: Government institutions, big industry vendors and manufacturers, RAPDASA, educational institutions, and software developers.

- **Government institutions**

The overwhelming response was that the government has a big role to play in the adoption of AM, particularly the CSIR (Council for Scientific and Industrial Research) and the IDC (Industrial Development Corporation), as illustrated by the following respondent comments:

- 'I think CSIR is quite the big player as well because they invest a lot of funding into metal, 3D printing and novel new additive manufacturing systems.' - **Managing director**
- 'But the IDC is where the money flows from.' – **Managing director – designer**

- **Eskom**

It was also noted by a few participants that the load-shedding or lack of electricity supply that South Africa is experiencing for a decade is affecting the uptake of AM. An AM process that can take up to eight hours to create a part cannot have a loss of power during the process or the part being manufactured will break down, losing money and production time in the process. The loss in manufacturing productivity in South Africa, due to load shedding, has been noted in the literature (Dewa et al., 2020).

- **RAPDASA (Rapid Product Development Association of South Africa)**

Another overwhelming response by the participants was that the RAPDASA organisation, which is the mouthpiece of the AM industry in South Africa, is active in the industry to promote AM across the country. There was a positive response towards RAPDASA by the interviewees. The organisation was mentioned a few times as organising meetings and gatherings and being a centre for information.

- **Big industry vendors, manufacturers**

The adoption of AM is seen to be active in the dental industry. Other industries that are adopting AM, albeit at a lower intensity, are aerospace, automotive and power generation. Although the dental market is seen as the biggest adopter of AM, one respondent mentioned that it is still an untapped space.

- **Educational Institutions**

Educational institutions were seen as not doing enough to promote AM in the country. Due to them being subsidised by the government, they can have state-of-the-art equipment, although the concern was raised that one university with government-subsidized equipment was competing commercially in the industry.

- **Software developers**

Software is an important part of the AM industry and is poised to become an even more important player in the future, particularly custom software. This was also noted in the literature review (van der Zee & Rehfeld, 2015).

It is evident that the AM industry is influenced by multiple stakeholders from the private and public sectors. Development of the industry would require significant collaboration from the stakeholders given the different agendas of each.

4.4 Drivers of additive manufacturing adoption

Participants were asked what was driving the adoption of AM in the South African commercial sector. The main drivers mentioned were cost savings, the need to exploit South Africa's significant titanium reserves, localisation in manufacturing and the ability to protect local IP. Various other drivers were also mentioned by the interviewees: Low-volume production was a prominent issue, which has two important aspects. Firstly, the South African market is not large enough. Hence, there is a need to manufacture items at reasonable prices and low volume, which is difficult with conventional techniques. Secondly, in the tool manufacturing business, there is often a need to redesign a tool, as the needs of the industry are changing rapidly or because of an error in the tool's design, meaning that the design must be updated and put into production as quickly as possible. This need to produce prototypes rapidly and at a low cost has been found internationally (Gibson et al., 2021). The general need to reduce part costs and production times also drives the need to adopt AM, as shown in the respondent's comment below:

- ‘Getting to a point where we can reduce the cost of additive manufacturing parts by increasing production rates. I think that's one of the big drivers at this point in time, is the cost of additive manufacturing part[s]. So, I think [it] actually works well on very niche applications, where you can afford that type of component. But, if you can reduce the cost of an additive manufactured part, then you increase the number of applications it's viable for them.' **Managing director/researcher**

Due to South Africa's geographical position, importation is costly and time-inefficient, which has created a need to develop and adopt technologies locally to provide for local needs. This became apparent during the Covid-19 pandemic. Delivery times at South African customs impact the time it takes for products to be imported. This was corroborated by a start-up in South Africa during the pandemic (Cape Innovation and Technology Initiative, 2020). South Africa started making 3D-printed parts for respiratory systems to counter the lack of such equipment on the market, due to high demand (Dzogbewu et al., 2022).

5. Managerial Implications

Management education

The managerial implications for organisations are to ensure that the critical success factors for the adoption are addressed internally and externally. The implementation of AM strategies will require an innovative approach from management, ensuring that a culture of identifying and exploiting opportunities for AM applications are encouraged and pursued.

This will require the addition of technological and creative skills in the organisation, as well as education and training in the benefits and utilisation of AM. Investing in the education of management and technical teams towards the strengths and weaknesses of AM can lead to a clearer decision about its adoption. Moreover, companies in the design industry must invest in education on the new mindset that is required while designing for AM.

Culture of innovation

Fostering a culture of innovation at many levels within the organisation is vital if a change of mindset is to happen, to fully embrace the full potential of additive manufacturing.

Exploration of new markets

For organisations, it is recommended to explore new niches that can benefit from AM. The dental and medical markets must be explored in greater depth as their full potential has not been exploited yet, while further local and international opportunities can be developed.

Regulations

Organisations and companies should advocate for regulations and standards. Collaborating with the governing bodies will help with issues of intellectual property, standards, safety and quality control.

Finance and business models

Management should work towards addressing financial barriers, develop new business models, explore partnerships and find ways to reduce the financial barriers to entry.

Software development

Investing in software companies to develop and promote specialised solutions for AM applications is vital to leverage the power of AM.

Infrastructure stability

Finally, team leaders should find ways to address instabilities related to infrastructure, such as load-shedding, to improve the viability of AM locally.

6. Conclusions, Limitations and Future Research

6.1 Conclusions to the Research Questions

RQ1: Critical success factors in the adoption of AM

Table 10 below summarises and compares the literature review and the findings from the interviews:

Table 10: Critical success factors in the adoption of AM

Literature Findings	Research Findings	Conclusion
Technology: Capacity for rapid prototyping and production	This is being done in South Africa at research and production levels.	Identified and elaborated on
Technology: Customisation capacity, flexibility of design, creating complex designs	The knowledge to make new complex design is very limited locally. Only a few of the bigger institutions have the know-how. The knowledge exists in the medical/dental and partly in the aerospace fields.	Identified and elaborated on
	Uncertainty in doing business in SA: The unstable political climate drives away potential investors. Load shedding is a major problem for AM manufacturers and the machines cannot endure electricity cuts while in operation. The unstable and weak rand makes machines and materials expensive.	**New finding**
Technology: Cost-effective manufacturing and non-wastage of materials		Not identified
Knowledge: Skills of managers, technicians, and developers at firms	Managers and leaders are not aware of the real benefits of AM.	Identified and elaborated on
Technology: Build-speed time and electricity requirements	The build-time was seen as an impediment. The electricity requirements for industrial metal printers are quite significant and cannot operate during load-shedding; less significant for smaller printers but still cannot have a power break.	Identified and elaborated on
Knowledge: Education in primary,	Knowledge about AM is also lacking at the primary, secondary and tertiary education levels.	Identified and elaborated on

secondary, tertiary education and continuous education	Continuous education is also not enough.	
Technology: Capacity to create parts at a certain quality	The quality of parts differs in industries. In the medical/dental fields/aerospace field, there are high-quality standards to be met.	Identified and elaborated on
Technology: Adoption of international standards for manufactured parts	International Standards in AM manufacturing have not been widely adopted in SA. Local policies in SA are not doing enough to tackle this issue.	Identified and elaborated on
Technology: Cost of raw materials and cost of AM printers	An important factor in the adoption of AM. Many companies do not want to invest due to high initial costs. Raw materials are expensive, mostly imported, significantly increasing their costs.	Identified and elaborated on
Regulation: Intellectual property Issues	Big companies have fewer IP issues than smaller ones. Smaller companies have difficulty protecting their IPs.	Identified and elaborated on
Knowledge: change in mindset	Not enough focus on the mindset needed to design for AM.	Identified and elaborated on
Financing:	Getting into the AM business is very costly and needs a solid business plan. A large initial investment is required.	Identified and elaborated on
Market:	The market was seen as being small but with a lot of potential for growth.	Identified and elaborated on

Most of the factors found in the literature were also mentioned during the interviews, with the addition of the new factor being the uncertainty of doing business in South Africa impacting investors.

RQ2: Role Players

As seen from the interviews, the government needs to have a bigger role in encouraging industries to adopt AM, if the policy for 4IR in South Africa is to succeed. The load-shedding problem at Eskom is also a major problem with manufacturing industries in SA, especially for AM. The non-engagement of the government with the industry is seen as hurting the AM sector. Investors are reticent to invest in South Africa due to political instability and prefer to invest elsewhere. More work is also needed in adopting international standards in the AM industry.

Universities and other institutions are also not seen as doing enough to educate students about AM. It was also noted that teachers do not have enough training and the school curriculum needs to be adjusted as well. The dental and aerospace industries are well established but the market is still untapped. RAPDASA is seen as being active in the promotion of AM.

Software development is a big part of the AM industry and had big potential in South Africa. There is already some software development happening locally, but it is still a niche market. Software for these niche markets could potentially be an important leg in AM research and development in SA. At the present, most of the software is imported and expensive.

RQ3: Drivers for AM adoption

Table 11 below summarises and compares the literature review and the findings from the interviews.

Table 11: Drivers for AM adoption

Literature Findings	Research Findings	Conclusion
Cost and time savings	Need to cut imports and create locally due to the weak and fluctuating rand. AM can help with this.	Identified and elaborated on
Use of South Africa's Titanium reserves	SA has big reserves of Titanium that need to be exploited.	Identified and elaborated on
	Need to manufacture locally due to unforeseen circumstances, such as the COVID-19 pandemic, which destabilized many international supply chains.	**New finding**
	The ability to protect local IP, by developing software in-house.	**New finding**

6.2 Theoretical contribution: application of the T-O-E framework

The Technology–Organisation–Environment framework developed by Tornatzky and Fleischer (1990) and subsequently enhanced by Miscione and Johnston (2010) can be applied to examine the adoption of AM, to analyse a firm's processes in adopting and implementing technological innovations, linking these decisions with contextual factors, as illustrated in Figure 4.

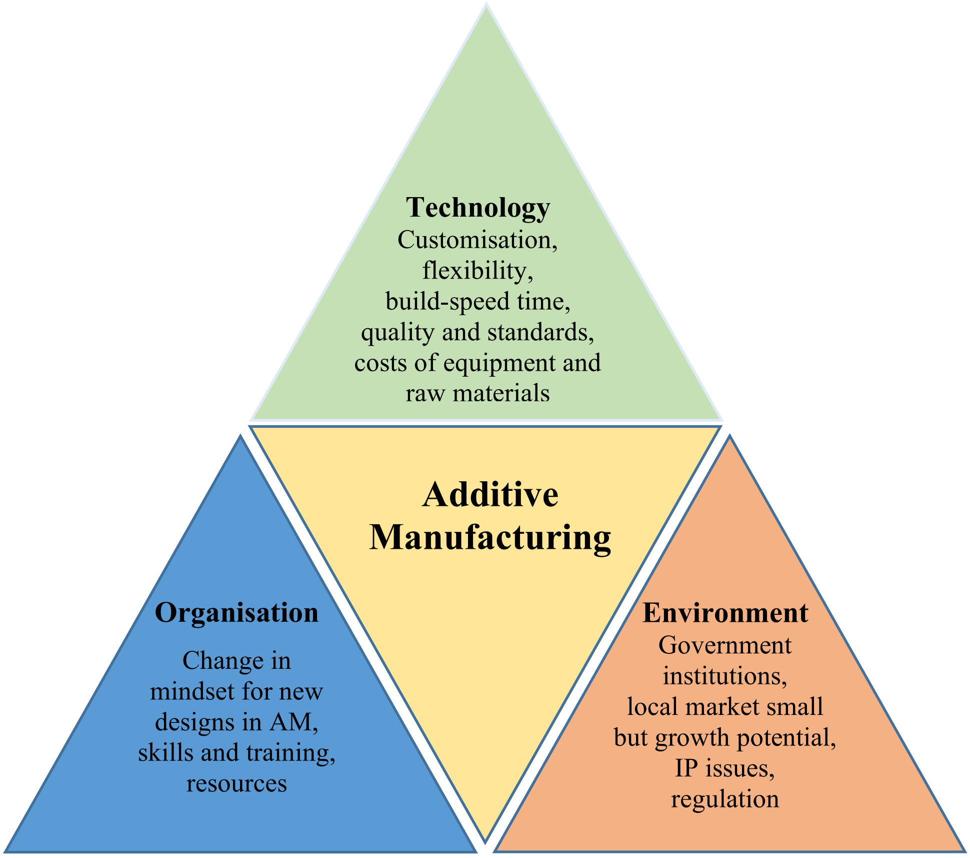

Figure 4. The Technology–Organisation–Environment framework applied to the AM industry (Miscione & Johnston, 2010)**.**

The critical factors that can affect AM adoption are appropriately categorised in this framework and provide guidance for the development of the industry by addressing these factors and contextual issues.

6.3 Limitations and future research

The number of participants available for the interviews in this study was small, as AM is a new field in South Africa, and only experts with at least a few years of experience in the field were recruited. This ensured relevance and reliability. However, the small sample size could have resulted in biased results. In addition, as this was a qualitative study with a small sample size, results could not be generalised to the population.

As AM is still in its infancy, there are many avenues of future research in this field that can benefit the local AM industry:

- Conduct a quantitative survey of the success factors of AM in South Africa.
- Develop methods to quantify the costs associated with AM. This could give more realistic costs related to AM.
- Conduct a survey of open-source software available in the AM market and the state of AM-related software industry in SA. This is critical as software is an important pillar in developing new markets in the AM industry.
- Data on the regulatory and IP issues regarding AM is still lacking locally, so research in this field would be useful for both academia and industry.
- Conduct a longitudinal study to assess how the critical factors change over time in. This is relevant as the many facets of AM are still in the infancy stage.

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